Mon. Not. R. Astron. Soc. **000**, 1–26 (2009) Printed 24 March 2010 (MN LaTeX style file v2.2)

Spin Angular Momentum Evolution of the Long Period Algols

A. Dervişoğlu[1,2]⋆, Christopher A. Tout[2] and C. İbanoğlu[1]

[1] *Ege University, Science Faculty, Astronomy and Space Sciences Dept., 35100 Bornova, İzmir, Turkey*

[2] *Institute of Astronomy, The Observatories, Madingley Road, Cambridge CB3 0HA*

Accepted 200x December 15. Received 200x December 14; in original form 1988 October 11

ABSTRACT

We consider the spin angular momentum evolution of the accreting components of Algol-type binary stars. In wider Algols the accretion is through a disc so that the accreted material can transfer enough angular momentum to the gainer that material at its equator should be spinning at break-up. We demonstrate that even a small amount of mass transfer, much less than required to produce today's mass ratios, transfers enough angular momentum to spin the gainer up to this critical rotation velocity. However the accretors in these systems have spins typically between 10 and 40 per cent of the critical rate. So some mechanism for angular momentum loss from the gainers is required. Unlike solar type chromospherically active stars, with enhanced magnetic activity which leads to angular momentum and mass loss, the gainers in classical Algols have radiative envelopes. We further find that normal radiative tides are far too weak to account for the necessary angular momentum loss. Thus enhanced mass loss in a stellar wind seems to be required to spin down the gainers in classical Algol systems. We consider generation of magnetic fields in the radiative atmospheres in a differentially rotating star and the possibility of angular momentum loss driven by strong stellar winds in the intermediate mass stars, such as the primaries of the Algols. Differential rotation, induced by the accretion itself, may produce such winds which carry away enough angular momentum to reduce their rotational velocities to the today's observed values. We apply this model to two systems with initial periods of 5 d, one with initial masses 5 and 3 $M_{\odot}$ and the other with 3.2 and 2 $M_{\odot}$. Our calculations show that, if the mass outflow rate in the stellar wind is about 10 per cent of the accretion rate and the dipole magnetic field

is stronger than about 1 kG, the spin rate of the gainer is reduced to below break-up velocity even in the fast phase of mass transfer. Larger mass loss is needed for smaller magnetic fields. The slow rotation of the gainers in the classical Algol systems is explained by a balance between the spin-up by mass accretion and spin-down by a stellar wind linked to a magnetic field.

Key words: binaries: close, stars: evolution, stars: magnetic fields

1 INTRODUCTION

Evolution of single stars is now well modelled (see for example Pols et al. 1995). There remain concerns with mass loss, rotation and convection but appropriate and successful empirical treatments exist. Evolution of a binary star has several additional complications associated with interaction between the components. Since solving the mystery of Algol systems (Hoyle 1955; Crawford 1955), the prototype of semi-detached Algol-type binary stars with one evolved and one main-sequence component, we realize that there are some stages of evolution when interaction between the components is unavoidable. We must therefore take into account, in our calculations, the mass transfer and mass loss together with any angular momentum and magnetic interaction between the components, at least in some critical phases, to fully understand evolution of a binary system.

Over the last few decades, the evolution of Algols has been modelled with well defined approximations such as conservation of total mass and total orbital angular momentum. The effect of mass transfer on the structure of both stars can be modelled reasonably well. The angular momentum transfer during mass exchange, however, is not well understood. As we shall see in section 2.1 there are some episodes of mass transfer in Algols when accretion discs or disc-like structures form around the mass gainer.

Current approximations of binary star evolution do not adequately explain the spin angular momentum of the mass-gaining components because the high specific angular momentum of the disc material should easily spin these stars up to their critical break-up rotational velocities in less than the time needed to reverse the mass ratio of system and enter the Algol phase. Here we discuss formation of discs in classical Algol systems and consider the spin angular momentum evolution of mass accreting components, taking into account discs, tides and magnetic stellar winds. We demonstrate that tidal effects play a minor role in the

⋆ E-mail: ahmetdervisoglu@mail.ege.edu.tr

Table 1. The absolute parameters of Algol primary components (İbanoğlu et al. 2006). For each star, columns $2-8$ are the orbital period, mass ratio, masses, radii and inclination. Then $v_{\rm syn}$ would be the equatorial velocity of the mass gainer (star 1) if it were synchronous while $v_{\rm eq}\sin i$ is the measured projected velocity and $F = v_{\rm eq}/v_{\rm syn}$.

Name	P/d	q	$M_1/\mathrm{M}_\odot$	$M_2/\mathrm{M}_\odot$	$R_1/\mathrm{R}_\odot$	$R_2/\mathrm{R}_\odot$	i	$v_{\rm syn}\sin i$	$v_{\rm eq}\sin i$	F	Ref.
TW And	4.12	0.210	1.68	0.32	2.19	3.37	87	27	32	1.19	5
KO Aql	2.86	0.217	2.53	0.55	1.74	3.34	78	30	41	1.37	4
IM Aur	1.25	0.311	2.24	0.76	2.57	1.74	75	101	135	1.34	1
R CMa	1.14	0.170	1.07	0.17	1.50	1.15	80	76	98	1.29	1
S Cnc	9.48	0.090	2.51	0.23	2.15	5.25	83	12	174	14.5	5
RZ Cas	1.20	0.351	2.10	0.74	1.67	1.94	83	62	87	1.40	3
TV Cas	1.81	0.470	3.78	1.53	3.15	3.29	79	90	79	0.88	3
U Cep	2.49	0.550	3.57	1.86	2.41	4.40	88	56	437	7.80	3
RS Cep	12.4	0.145	2.83	0.41	2.65	7.63	87	11	170	15.4	1
XX Cep	2.34	0.150	2.03	0.33	2.12	2.25	85	46	47	1.02	2
U CrB	3.45	0.289	4.74	1.46	2.79	4.83	82	48	60	1.25	1
SW Cyg	4.57	0.190	2.50	0.50	2.60	4.30	83	22	196	8.91	3
WW Cyg	3.32	0.310	2.10	0.60	2.00	7.00	89	31	41	1.32	2
TW Dra	2.81	0.470	1.70	0.80	2.40	3.40	86	43	37	0.86	2
AI Dra	1.20	0.429	2.86	1.34	2.17	2.42	78	83	85	1.02	1
S Equ	3.44	0.130	3.24	0.42	2.74	3.24	87	40	52	1.30	4
AS Eri	2.66	0.110	1.92	0.21	1.57	2.19	80	29	36	1.02	5
RX Gem	12.2	0.254	4.40	0.80	4.80	7.00	85	20	157	7.85	2
RY Gem	9.30	0.193	2.04	0.39	2.38	6.19	83	13	70	5.38	5
AD Her	9.77	0.350	2.90	0.90	2.60	7.70	84	13	143	11.0	2
TT Hya	6.95	0.224	2.63	0.59	1.95	5.87	84	15	164	10.9	2
δ Lib	2.33	0.345	4.70	1.70	4.12	3.88	81	89	68	0.76	1
AU Mon	11.1	0.199	5.93	1.18	5.28	10.04	79	24	124	5.17	5
TU Mon	5.09	0.210	12.60	2.70	5.60	7.10	89	56	153	2.73	2
AT Peg	1.15	0.484	2.50	1.21	1.91	2.11	76	80	82	1.02	1
β Per	2.87	0.217	3.70	0.81	2.74	3.60	82	51	52	1.02	3
RW Per	14.2	0.150	2.56	0.38	2.80	7.30	81	10	161	16.1	3
RY Per	6.86	0.271	6.24	1.69	4.06	8.10	83	30	213	7.10	1
Y Psc	3.77	0.250	2.80	0.70	3.06	3.98	87	37	38	1.03	3
RZ Sct	15.2	0.216	5.50	1.50	11.00	14.00	83	36	222	6.17	3
V356 Sgr	8.89	0.380	12.20	4.70	8.50	15.40	85	48	212	4.42	1
V505 Sgr	1.18	0.520	2.68	1.23	2.24	2.17	80	85	101	1.19	1
U Sge	3.38	0.370	4.45	1.65	4.00	5.00	90	60	76	1.27	3
λ Tau	3.95	0.263	7.18	1.89	6.40	5.30	76	80	88	1.10	1
TX Uma	3.06	0.248	4.76	1.18	2.83	4.24	82	46	63	1.37	2
Z Vul	2.45	0.430	5.40	2.30	4.30	4.50	89	89	135	1.52	1

References: (1) van Hamme & Wilson (1990) , (2) Etzel & Olson (1993),(3) Mukherjee, Peters, & Wilson (1996), (4) Soydugan et al. (2007) and (5) Glazunova et al. (2008).

removal of excess angular momentum from the gainers and rely on a magnetically locked stellar wind to do this.

2 OBSERVATIONS AND MOTIVATION

Recently İbanoğlu et al. (2006) compiled and analysed 61 Algols for which the fundamental parameters are well known. In Fig. 1 we show locations of the primary and secondary components in the Hertzsprung-Russell diagram (HRD). We use the observers' convention and refer to the brighter, hotter and currently more massive star as the primary component with mass M_1 and the redder, mass losing component as the secondary with mass M_2.

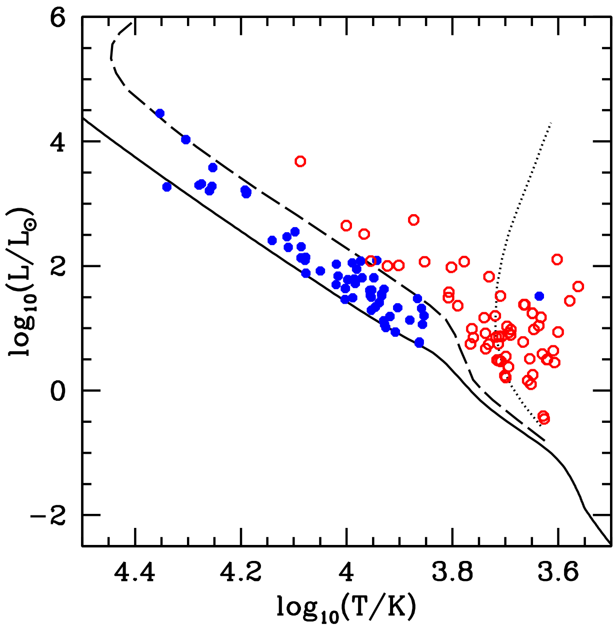

Figure 1. Locations of the components of the well known Algol systems in a Hertzsprung–Russell diagram. Dots and circles are the primary and secondary components, respectively. The zero-age main sequence (ZAMS, continuous), terminal-age main sequence (TAMS, dashed) and base of the giant branch (BGB, dotted) are as found by Pols et al. (1998).

İbanoğlu et al. (2006) arrived at several interesting observations concerning the relation between orbital angular momentum and mass.

(i) Semi-detached binaries (SDBs) with mass ratios $q = M_2/M_1 > 0.3$ and orbital periods of $P > 5\,$d have almost the same angular momentum as detached binaries (DBs). However the SDBs with short periods have lower angular momentum even when they have the same mass ratios.

(ii) The orbital angular momenta of SDBs with periods $P < 5\,$d and $P > 5\,$d are 45 and 25 per cent smaller, respectively, than those of DBs of a total mass of about $3\,M_\odot$.

(iii) The secondaries of SDBs with orbital periods longer than 5 d have angular momenta twice that of secondaries with the same mass but with a period shorter than 5 d.

(iv) The specific angular momenta of systems with $P > 5\,$d are about 24 per cent larger than those of the systems with $P < 5\,$d for primary components of the same mass. More extremely the specific angular momenta of the longer period systems are 65 per cent greater than those of the shorter period systems with the same mass secondary star.

These results suggest that different mechanisms govern angular momentum evolution for short and long period SDBs. Absolute parameters and projected rotational velocities measured with great accuracy are given for some Algols in Table 1. The spins of the primary stars in SDBs show a marked distinction between short and long period systems at an orbital

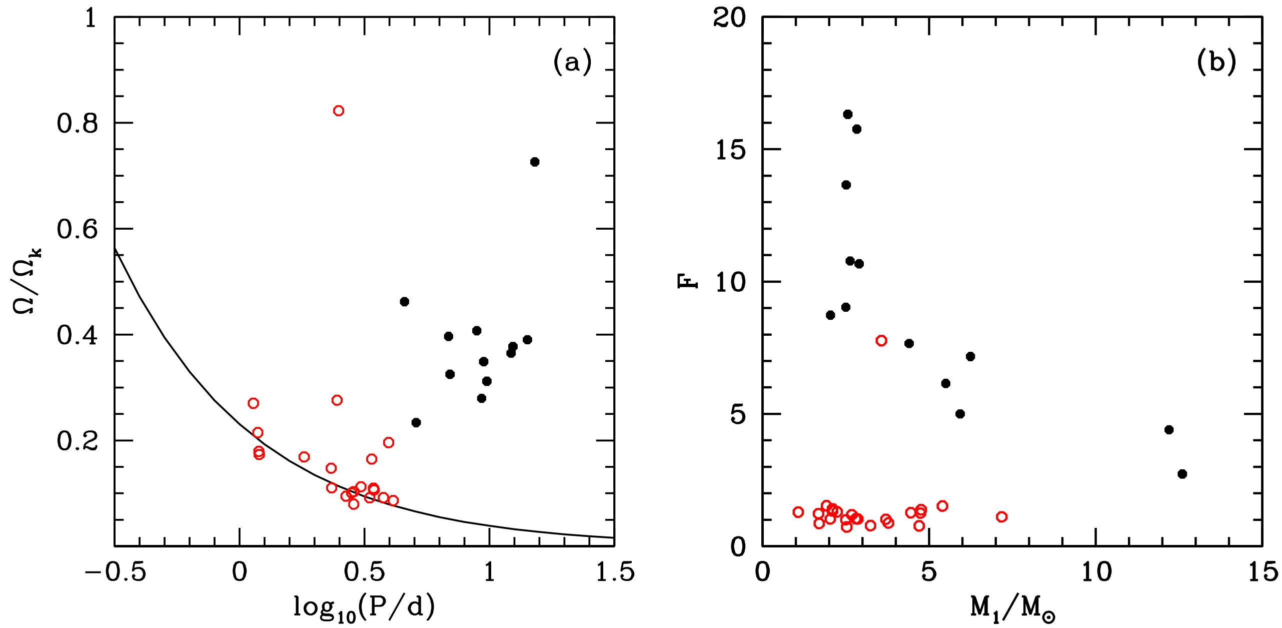

Figure 2. (a) The ratios of spin angular to Keplerian angular velocities for the mass accreting primaries of the semi-detached binaries are plotted against their orbital periods. The solid line is the synchronous value at that period. (b) The ratios of the observed equatorial to the computed synchronous rotational velocities, $\mathrm{F} = \mathrm{v_{eq}}/\mathrm{v_{syn}}$, for the same stars are plotted against the mass of the gainer. Open circles and solid dots represent the SDBs with periods $P < 5\,\mathrm{d}$ and $P > 5\,\mathrm{d}$, respectively. There is a marked difference above and below $P = 5\,\mathrm{d}$. At shorter periods the accretors are close to synchronous, while at longer periods they tend to spin somewhat faster.

period of about 5 d (Eggleton 2006) as we show in Fig. 2. This indicates that the observed rotational velocities of the primaries are far from synchronized with the orbit in longer period systems, $P > 5\,\mathrm{d}$. The main discriminator of the high rotational velocity of a gainer in a classical Algol appears to be its orbital period, independent of its mass. However, if we consider only long period Algols, the spin rate appears to decrease as the mass of the gainer increases. It should be noted that the gainer in U Cep seems to rotate faster than other short-period Algols despite its 2.5 d orbital period. Photometric and spectroscopic observations indicate that this system shows transient disc because the eclipse durations vary from time to time (Gimenez 1996; Manzoori 2008). It shows variations in both orbital period and total luminosity consistent with mass transfer and convective activity. This slightly anomalous behaviour is probably due to the mass ratio in U Cep being very close to the critical mass ratio at which mass transfer proceeds dynamically (Tout & Hall 1991).

The above results led us to reconsider tidal interaction and angular momentum transfer in systems in which mass transfer is still occurring. A number of angular momentum loss mechanisms (Packet 1981; Eggleton 2000; Chen, Li & Qian 2006) have been suggested to explain the evolution of Algols but none is entirely satisfactory. In any case, it is well estab-

lished that accretion discs can be formed in phases of evolution when the relative radius of the mass accreting star is small enough.

2.1 Accretion Discs

Classical Algols are semi-detached interacting eclipsing binary stars in which the less massive, evolved secondary component (spectral type F or later G and luminosity class of giant or sub-giant) has expanded enough to fill its Roche lobe. These less massive cool secondaries are transferring material through a gas stream on to a B or A spectral-type main-sequence primary component. In the long period, $P > 5\,\mathrm{d}$, Algols the mass gaining components are small enough, relative to the binary separation, that mass transfer takes place through an accretion disc. The in-falling material has too much angular momentum for the stream to directly impact on the accretor. Lubow & Shu (1975) examined the condition for the formation of discs in semi-detached systems by modelling the stream as a ballistic flow from the inner Lagrangian point. As seen in Fig. 3a (similar to fig. 4 of Lubow & Shu 1975), if the minimum distance of the stream from centre of the gainer $a\varpi_{\mathrm{min}}$ is smaller than the radius of detached component (R_1) the transferring material can impact directly on its surface. This impact leads to the formation of variable accretion structures. Otherwise, when $a\varpi_{\mathrm{min}} > R_1$, the mass flow misses the star and collides with itself at a larger radius. Radial motion is dissipated and the resulting ring of material spreads viscously to form a permanent accretion disc of radius $a\varpi_{\mathrm{d}}$. If the accretor has a radius between $a\varpi_{\mathrm{min}}$ and $a\varpi_{\mathrm{d}}$ a disc could exist because it could intercept the stream before it impacts the star. In such a case the disc could be transient. If $R_1 > a\varpi_{\mathrm{d}}$ then the stream must impact the star directly. Expressing these distances relative to the separation a, we can predict the presence of discs in semi-detached systems. Both ϖ_{min} and ϖ_{d} are functions only of mass ratio q. The majority of Algols with $P > (4-5)\,\mathrm{d}$ are within the region (Fig. 3b) where we expect stars to have either a permanent or transient disc.

Indeed the presence of a disc around the gainer is easily confirmed with optical spectra of the primary star. Richards & Albright (1999) observed and analysed optical spectra of Algols and demonstrated that those with periods $P > (4-5)\,\mathrm{d}$ show double-peaked Hα emission, characteristic of accretion discs, while those of shorter periods show only single-peaked emission, characteristic of a mass stream structure (fig. 3 of Richards & Albright 1999).

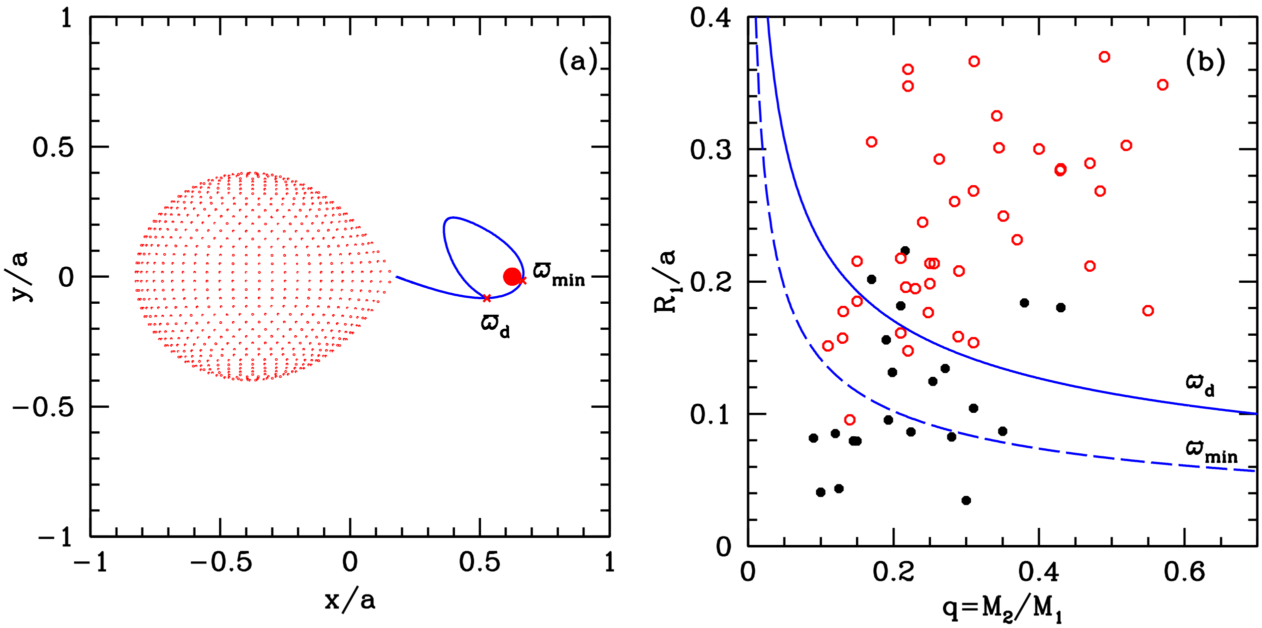

Figure 3. (a) The orbit of the mass flow in a semi-detached system with masses $5\,M_\odot$ and $3\,M_\odot$ and an orbital period of 5 d. The coordinates x and y are scaled to the orbital separation a and are in the the equatorial plane of the binary, perpendicular to the axis of rotation and in a frame corotating with the system. The mass stream trajectory is calculated with Flannery (1975)'s approximations. (b) The positions of all well known Algol primary stars in a fractional radius against mass-ratio diagram. The radii below which a disc must form $\varpi_{\rm min}$ and below which a disc may form $\varpi_{\rm d}$ are indicated. The solid dots are the gainers with permanent accretion discs among the long period Algols.

It is thus well established, both observationally and theoretically, that long period Algols develop a permanent or transient accretion disc or disc-like structure during mass transfer. In the next section we examine angular momentum transport and loss mechanisms to explain the asynchronous rotational velocities of detached components in the presence of discs or disc-like structures.

3 MODELS

In accretion disc theory, the in-falling matter first forms an accretion ring. Stothers & Lucy (1972) proposed a model in which the accreting star is driven into differential rotation by the presence of such a ring or disc around it. Viscous forces transfer most of the angular momentum (AM) to the outer edge of the ring while mass falls inwards. The ring spreads out. Eventually a disc forms and this allows the matter at the inner edge to fall on to the surface of the star. For such a Keplerian disc, the angular velocity $\Omega_{\rm k}$ of material at radius R is given by

$$\Omega_{\rm k}^2 = \frac{GM}{R^3}, \tag{1}$$

where G is Newton's gravitational constant and the M is the mass of the accreting star. Hence, the specific angular momentum of accreted material at the surface of the star, of radius R, is

$$h_{\rm d} = \sqrt{GMR}. \tag{2}$$

This specific angular momentum of accreted material would be equal to that at the equator of the gainer if it were critically rotating at brake up. It is much larger than found in normal stars. When accreting at a rate $\dot{M}_{\rm acc}$ the rate of angular momentum transferred from the disc to the star is

$$\frac{dJ_{\rm acc}}{dt} = \dot{M}_{\rm acc}\sqrt{GMR}. \tag{3}$$

Assuming a negligible change in stellar radius, we can determine the amount of mass ΔM that must be transferred through the disc to spin the star up to its critical angular velocity $\Omega_{\rm k}$ from an initial Ω_0 when it had mass M_0. Let the radius of gyration of the star be kR so that its total angular momentum is $k^2MR^2\Omega$ when spinning rigidly at Ω then

$$\Delta M = \frac{k^2}{1-k^2}\left(1-\frac{\Omega_0}{\Omega_{\rm k}}\right)M_0. \tag{4}$$

A more precise formula was derived by Packet (1981) who took account of the change in the mass of the star but this is unnecessary for our purposes because ΔM is always small. For main-sequence stars $k^2 \approx 0.1$ and varies little. Thus when $0.1 < \Omega_0/\Omega_{\rm k} < 0.4$ we find $0.1 > \Delta M/M_0 > 0.06$. This is very small when we consider that all classical Algols have a mass ratio of $q < 0.7$ (mostly $q \approx 0.2$ according to İbanoğlu et al. 2006) which indicates that the losers in the classical Algols have transferred more on the order of $1\,{\rm M}_\odot$. The shaded area in Fig. 4 shows the amount of material that must be accreted from a disc to spin the star up to its critical rotational velocity. Despite having high spin velocities, $0.1 < \Omega/\Omega_{\rm k} < 0.4$, observations show that the detached components in most of the Algols do not actually attain their critical rotational velocity (Table 1, Fig. 2a). The only exception, with the high ratio of $\Omega/\Omega_{\rm k} = 0.72$, is RZ Sct. This star's radial velocity curve is distorted (e.g McNamara 1957). It shows emission in H_α outside eclipse (McNamara 1957; Hansen & McNamara 1959) and its light curve displays distortions due to an accretion stream (Olson & Bell 1989). These observed phenomena may be taken as the signature of a rapid mass transfer phase.

In all cases a mechanism is needed to dissipate this excess angular momentum, along with associated energy. Here we examine various mechanisms for angular momentum loss and compare with the observations.

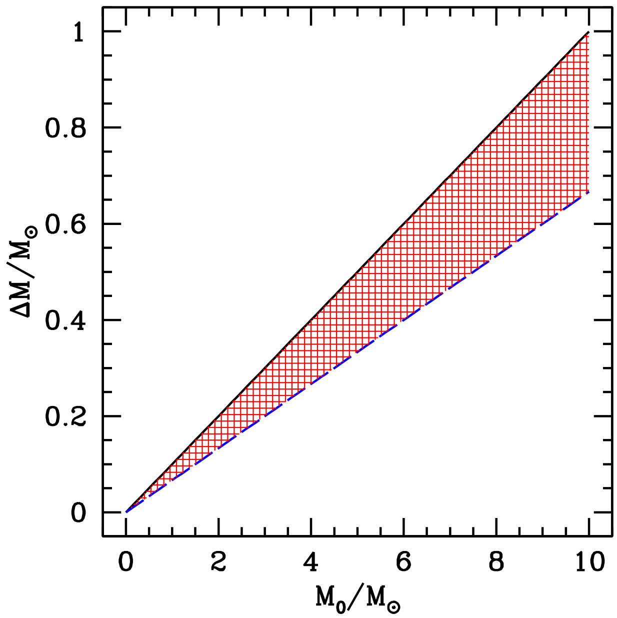

Figure 4. The amount of accreted mass needed to spin a star with initial mass of $M_0/\mathrm{M}_\odot$ up to its critical rate Ω_k when initially $\Omega_0 = 0.1\Omega_\mathrm{k}$ (solid line) and $0.4\Omega_\mathrm{k}$ (dashed line).

3.1 Tidal Forces and Energy Dissipation Mechanisms

Tidal forces have been quantified since the work of Darwin (1879) and are, perhaps, the most well understood mechanism for angular momentum transfer within binary stars. Tidal interactions exchange angular momentum between the orbit and stellar spins by torques. They act to synchronize stellar spins with the orbital period. According to Zahn (2005) the time-scale for synchronization t_sync is given by

$$\frac{1}{t_\mathrm{sync}} = -\frac{1}{\Omega - \omega}\dot{\Omega} \approx \frac{1}{t_\mathrm{diss}} q^2 \frac{MR^2}{I}\left(\frac{R}{\mathrm{a}}\right)^6, \tag{5}$$

where ω is orbital angular velocity, a is separation of system, $I = k^2MR^2$ is the moment of inertia of the primary star and t_diss is the time-scale for the most effective dissipation mechanism. It depends on the stellar type. For stars with convective envelopes the kinetic energy of the equilibrium tides is dissipated by turbulent convective eddies. For those with radiative envelopes the shortest time-scale is through gravity wave dissipation. It is well known that the energy dissipation in convective envelopes is much more effective than in radiative envelopes (Zahn 2005).

As we shall describe in the details of the binary star evolution models in section 3.2, we have examined the efficiency of the tidal torque at opposing the spinning up effect of accreted material from a disc. Gainers in Algol systems are early type stars, so we take the approximation of the dynamical tide with radiative damping given by Hurley, Tout & Pols

(2002) to evaluate $t_{\rm diss}$ for equation 5. In the classical evolution of an Algol the initially more massive star evolves more quickly, overfills its Roche lobe and begins a phase of rapid mass transfer soon after it departs from the main sequence as it rapidly becomes a giant star. The primary star is at this time relatively compact and substantially smaller than its companion so that an accretion disc is likely to form. When the accretion is conservative and uniform over time, so that the rate of accretion from the disc to the gainer ($\dot{M}_{\rm acc}$) is the same as the mass-loss rate from the donor ($\dot{M}_2$), we can calculate the spin angular momentum gained during mass transfer. Initially the angular momentum of the gainer is

$$J_{\rm s0} = k^2 M R^2 \Omega_0 \,. \qquad (6)$$

The net change depends on the competition between the torque of accreted material (equation 3) and the opposing spin-down torque of tides obtained from equation 5, by

$$\left(\frac{dJ}{dt}\right)_{\rm tid} = k^2 M R^2 \dot{\Omega}, \qquad (7)$$

where k remains approximately constant. In Fig. 5 we show the variation in the angular velocity of a gainer undergoing mass accretion through a disc with its increasing mass. We used a detailed evolution model for a system of stars initially of masses 5 and 3 $\mathrm{M}_\odot$ and an orbital period of $P = 5$ d. We allow the star to rotate faster than its break-up rate for illustration only. We find tides are almost incapable of synchronizing the star with the orbit because the gainer reaches brake-up velocity after accreting only a small amount of matter as indicated by equation 4. We found that, to affect the star's spin, the tides would need to be stronger by more than a factor of 10^7. There is no known physical basis for this. We might also hope that a convective core's ability to dissipate energy by tidal forces may have an effect but the strong dependence of the synchronization time on $(R/a)^6$ in equation 5 means that the contribution of the convective core is too small and may be neglected. Thus we conclude that tides are insufficient to synchronize the stellar spin of the gainer with the orbit when accretion is through a disc.

3.2 Magnetic Winds

Our analysis has shown that tides are insufficient to dissipate the excess angular momentum accreted by Algol primaries with discs. So we consider alternatives that are applicable to this case. The total angular momentum lost from a star in a wind coupled to a magnetic field is equivalent to angular momentum carried away by the wind material co-rotating up to the Alfvén surface (Weber & Davis 1967; Mestel 1968). So the rate of change of angular

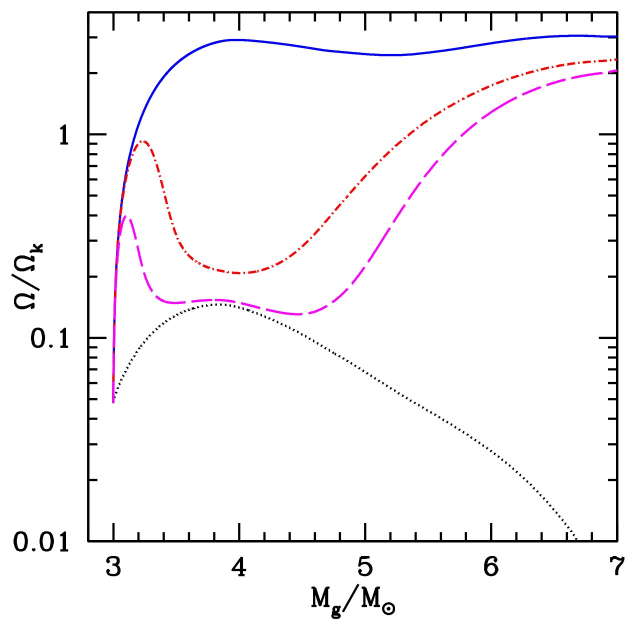

Figure 5. Spin evolution of a gainer in a binary with initial masses of $5+3\,\mathrm{M}_\odot$ and a period of $P = 5\,\mathrm{d}$ in the case when total mass and angular momentum are conserved. Calculations were made for standard tides (equation 5, solid line) and tides increased by factors of 10^7 (dot-dashed line) and 10^8 (dashed line). The fully synchronous case (dotted line) is plotted for comparison.

momentum of the star owing to the wind is

$$\left(\frac{dJ}{dt}\right)_{\mathrm{w}} = \dot{M}_{\mathrm{w}} R_{\mathrm{A}}^2 \Omega, \tag{8}$$

where Ω is the angular velocity of the star and R_{A} is the Alfvén radius at which outflow speed equals the local magnetic Alfvén speed

$$v_{\mathrm{A}} \approx \frac{B_{\mathrm{A}}}{\sqrt{4\pi\rho_{\mathrm{A}}}}, \tag{9}$$

where ρ_{A} is the density of wind material, B_{A} is the magnetic field strength at the Alfvén surface and $\dot{M}_{\mathrm{w}} < 0$ is the mass-loss rate. For a spherical outflow

$$\rho_{\mathrm{A}} \approx \frac{-\dot{M}_{\mathrm{w}}}{4\pi R_{\mathrm{A}}^2 v_{\mathrm{A}}}. \tag{10}$$

The angular momentum loss rate depends on the field structure and flow velocity which are not easily determined a priori for the wind. We need to make assumptions about both. To model the magnetic field structure in a simple manner, we assume that field strength follows a single power law of the form

$$B_{\mathrm{A}} = B_{\mathrm{s}}(R/R_{\mathrm{A}})^n, \tag{11}$$

where n describes the geometry of the stellar field and $n = 3$ corresponds to a dipole field (Weber & Davis 1967; Mestel & Spruit 1987) while B_{s} and B_{A} are the magnetic flux densities at the stellar surface and at the Alfvén radius, respectively.

It is usually assumed that the thermal wind velocity is of the order of the escape velocity

(Tout & Pringle 1992; Stępień 1995) so that

$$v_{\rm A} \approx \sqrt{\frac{2GM}{R_{\rm A}}}. \tag{12}$$

Combining equations 12, 11, 10 and 9 we find equation 8 becomes

$$\frac{dJ_{\rm w}}{dt} = -\left((-\dot{M}_{\rm w})^{(4n-9)} B_{\rm s}^8 (2GM)^{-2} R^{8n}\right)^{\frac{1}{4n-5}} \Omega. \tag{13}$$

The second and considerable torque arises between star and disc by magnetic interaction. The framework of such an interaction was constructed by Ghosh & Lamb (1978). Some of the stellar magnetic dipole flux connects to the accretion disc and transports angular momentum between star and disc. We use the expression given by Armitage & Clarke (1996) and assume, as did Stępień (2000, 2002), that the radius of magnetosphere is equal to the co-rotation radius,

$$R_{\rm cor} = (\frac{\Omega}{\Omega_k})^{-2/3} R. \tag{14}$$

As they pointed out the disc torque does not depend on the mass of the disc so

$$\frac{dJ_{\rm disc}}{dt} = -\frac{\mu^2\Omega^2}{3GM}, \tag{15}$$

where $\mu = B_{\rm s}R^3$ is the magnetic moment of stellar magnetic field. Contrary to Stępień (2002) who assumes magnetic flux is constant, we assume that the magnetic field strength $B_{\rm s}$ remains constant because the mass of the accreting star increases at a substantial rate ($\dot{M}_{\rm acc} \approx 10^{-5}\,{\rm M}_\odot\,{\rm yr}^{-1}$). We seek a solution for various fiducial values of $B_{\rm s}$.

The third torque, the accretion torque discussed in section 3, has the effect of spinning-up the mass-accreting star. Now we replace the radius of the star R in equation 3 with $R_{\rm cor}$ because the stellar magnetic field disrupts the disc at $R_{\rm cor}$ as constant at the value of co-rotation radius.

The wind mass-loss rate remains an unknown parameter. Although there is no a priori rate we can set an upper limit. All observed Algols show reversed mass ratio so much of the material lost by the donor must be accreted by the gainer. We may write

$$\dot{M}_{\rm acc} \approx \beta \dot{M}_2 \tag{16}$$

and

$$\dot{M}_{\rm w} \leq (1-\beta)\dot{M}_2 = \frac{(1-\beta)}{\beta}\dot{M}_{\rm acc}, \tag{17}$$

where $0 < \beta < 1$. For conservative evolution $\beta = 1$. Matt & Pudritz (2005) claimed that the mass outflow rate in stellar winds is about 10 per cent of the accretion rate for the pre-mainsequence stars, corresponding to $\beta \approx 0.9$. This is why the classical T Tauri stars spin at less than 10 per cent of their breakup velocity. It is the original suggestion by

Hartmann & Stauffer (1989) that about one tenth of accreted material lost in a wind can remove the accreted angular momentum.

Such models have already been applied to a wide variety accreting stars including the pre-mainsequnce stars (Matt & Pudritz 2005, 2008a,b) and the Ap and Be stars (Stępień 2000, 2002). Both $\dot{M}_{\mathrm{acc}}$ and $\dot{M}_{\mathrm{w}}$ are taken as free parameters in most of these studies. In the case of binary evolution $\dot{M}_{\mathrm{acc}}$ depends on the orbital evolution which can be well modelled. So, for a given magnetic field, we need only make an estimate of the fraction of mass lost in the wind (equation 17) to estimate the angular momentum loss.

Like the tidal torque, which also depends strongly on the separation of binary, the magnetized wind and disc torques are very sensitive to changes in the radius R of the mass accreting star so a detailed evolutionary model is required. Here we use binary star models evolved with the Cambridge STARS code which was originally developed by Eggleton (1971). The physics was systematically updated by Pols et al. (1995) and the code has been modified so that it can evolve both components of a binary system simultaneously together with the effects of mass and angular momentum loss and transfer (Stancliffe & Eldridge 2009).

We have made various binary evolution models for two different initial systems, each with a period of 5 d and with masses $5 + 3\,\mathrm{M}_{\odot}$ and $3.2 + 2\,\mathrm{M}_{\odot}$. Such systems are believed to be the progenitors of Algol-type systems. We evolved both with $\beta = 0.9$, 0.7, 0.5 and 0.1. The code does not directly take into account the presence of a disc so we tabulate the output of the one dimensional structure of each component, the mass-transfer rate, accretion-rate and orbital parameters at every time step. From this we calculate the torque of the magnetic wind, the disc and the accretion and hence the resulting rotation rate for a given magnetic field strength. Because the variation in radius of the gainer is taken directly from the tables it is an approximation. It does not take account of possible rapid rotation. Typically the radius of an early-type non-rotating star depends on the mass as $R \approx M^{0.67}$ at solar metallicity (Maeder 2009). A rapidly rotating star becomes oblate. Its polar radius becomes smaller than that of the equatorial radius so that the equatorial radius, when rotating solidly at critical velocity is increased by a factor of 1.5 with respect to a non-rotating star of the same mass (Ekström et al. 2008). However when $\Omega/\Omega_k \approx 0.8$ this factor is only 1.1 and can be neglected when compared to the increase in radius as matter accretes.

To calculate the spin evolution of the mass accreting component we assume a dipolar ($n = 3$) magnetic field and that a magnetized wind is launched as soon as mass transfer

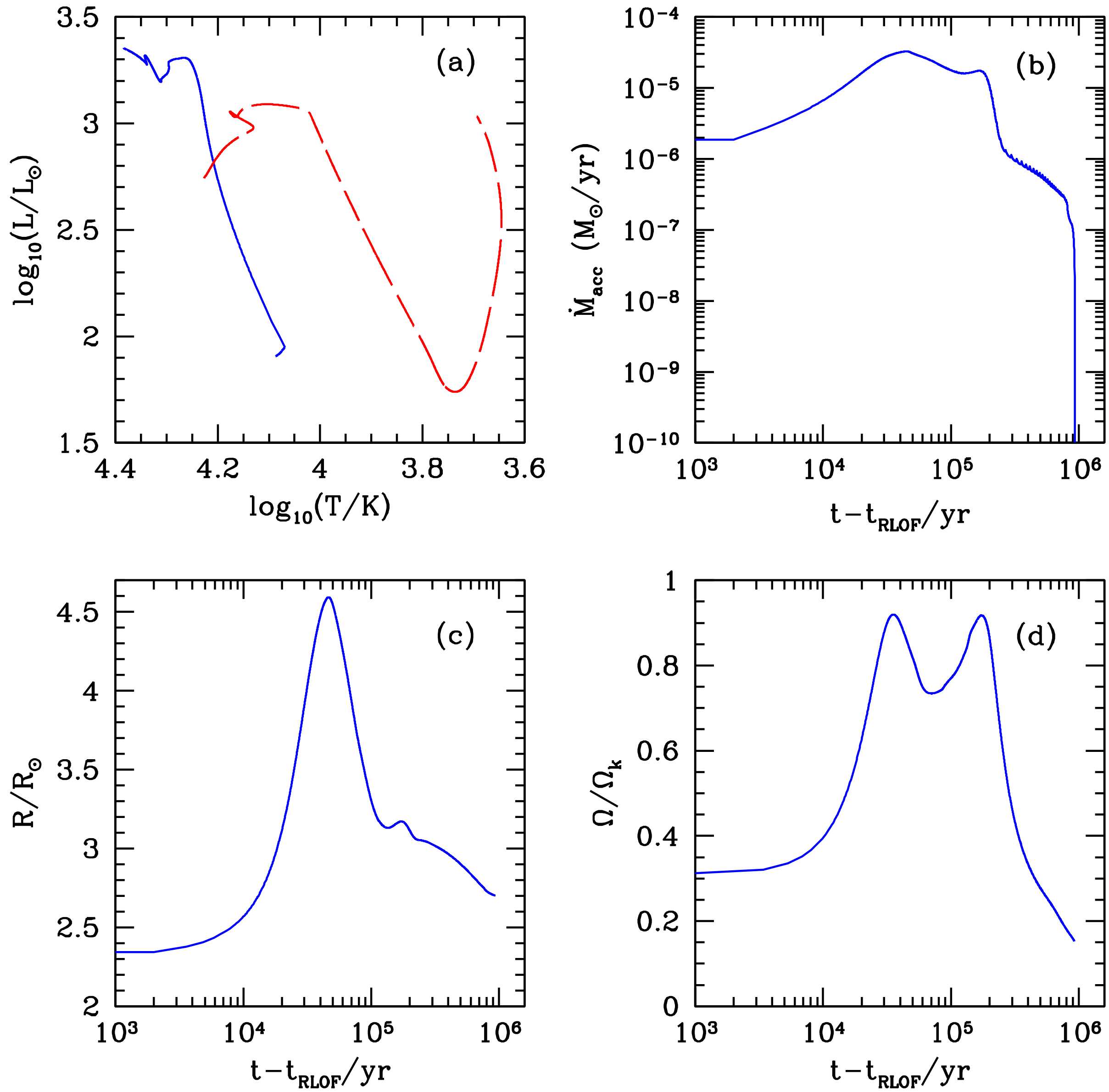

Figure 6. Evolution of a binary star with initial mass of 5 and 3 $M_\odot$ and orbital period of 5 d with $\beta = 0.9$ and $B_s = 1.5$ kG. In (a) the dashed line is the track of the initially more massive donor and the solid line that of the gainer in an Hertzsprung–Russell diagram. Panels (b), (c) and (d) show the accretion rate, radius and Ω/Ω_k of the gainer as a function of time since the onset of Roche lobe overflow (RLOF).

begins. We first obtain an evolutionary model of the given binary and each value of β. Then for various field strengths of B_s for each β we examine carefully how the angular velocity of the star changes as its mass increases. If the star never reaches its critical velocity the computation is ended. If, on the other hand, the star reaches its critical rotation rate we interrupt the mass accretion but allow the magnetic wind and disc torques to lower the angular velocity to less than the critical rate. This leads to an extra mass loss and a time

lag in the evolution of the system. When the gainer loses enough angular momentum that $\Omega/\Omega_k < 1$ mass accretion resumes.

In Fig. 6 we show the evolution of the system with initial masses 5 and $3\,\mathrm{M}_\odot$ and orbital period of 5 d. The $5\,\mathrm{M}_\odot$ star evolves off the main sequence when it exhausts hydrogen in its core and moves towards the Hertzsprung gap where it fills its Roche lobe and rapidly transfers most of its envelope to its less massive companion. It becomes established as a red giant when its mass has fallen to $0.67\,\mathrm{M}_\odot$. Our models show that this final mass is almost independent of β ($0.675\,\mathrm{M}_\odot$ for $\beta = 1$ falling to $0.665\,\mathrm{M}_\odot$ for $\beta = 0.5$). Meanwhile, the gainer moves up the main sequence as mass transfer proceeds. In Fig. 6a the dashed line is the evolutionary track of the $5\,\mathrm{M}_\odot$ and the solid line that of the $3\,\mathrm{M}_\odot$ star. The mass accretion rate $\dot{M}_{\mathrm{acc}}$ for $\beta = 0.9$ is plotted against time in Fig. 6b. It is larger during the early stages and slows sharply after 10^5 yr as the loser reaches the giant branch. The gainer reaches hydrostatic equilibrium on a dynamical time-scale and then thermodynamic equilibrium on the Kelvin–Helmholtz time-scale. The variation of the accreting star's radius over the same time interval is plotted in Fig. 6c and its angular velocity in Fig. 6d when the magnetic field strength is $B_{\mathrm{s}} = 1.5\,\mathrm{kG}$. Recall that the variation of angular velocity is caused by the interaction between the torques of the wind, the accretion and the disc together with radius changes of the star. After the phase of rapid mass transfer ($q \approx 0.2$) the slowing torques dominate. The location of the donor in the H–R diagram (see Fig. 1) shows that it is still at its minimum luminosity reached following mass transfer. For this system, this phase corresponds to an effective temperature of $\log_{10}(T_{\mathrm{eff}}/\mathrm{K}) = 3.66$ and luminosity of $\log_{10}(L/\mathrm{L}_\odot) = 2.25$.

The angular velocities computed for the same initial system but varying β and B_{s} are shown in Fig. 7. As expected a larger B_{s} creates larger torques for the same β and hence smaller angular velocities Ω/Ω_k at a similar point in the evolution. For the same B_{s} but smaller β there is more mass lost in the wind and again smaller Ω/Ω_k but then the evolution of the system is highly non-conservative. The most important result we find here is that when $B_{\mathrm{s}} \gtrsim 1\,\mathrm{kG}$ the gainer does not reach its critical spin rate if it loses 10 per cent of the mass transferred from its companion. In such a case a classical Algol as observed today is produced. For decreasing β the final mass ratio is larger for the same initial mass.

We also applied our models to a system with initial masses of $3.2 + 2\,\mathrm{M}_\odot$ and period $P = 5\,\mathrm{d}$. This is typical of the progenitors considered for Algol (β Per) itself (Tout et al. 1997). The models are shown in Figs. 8 and 9.

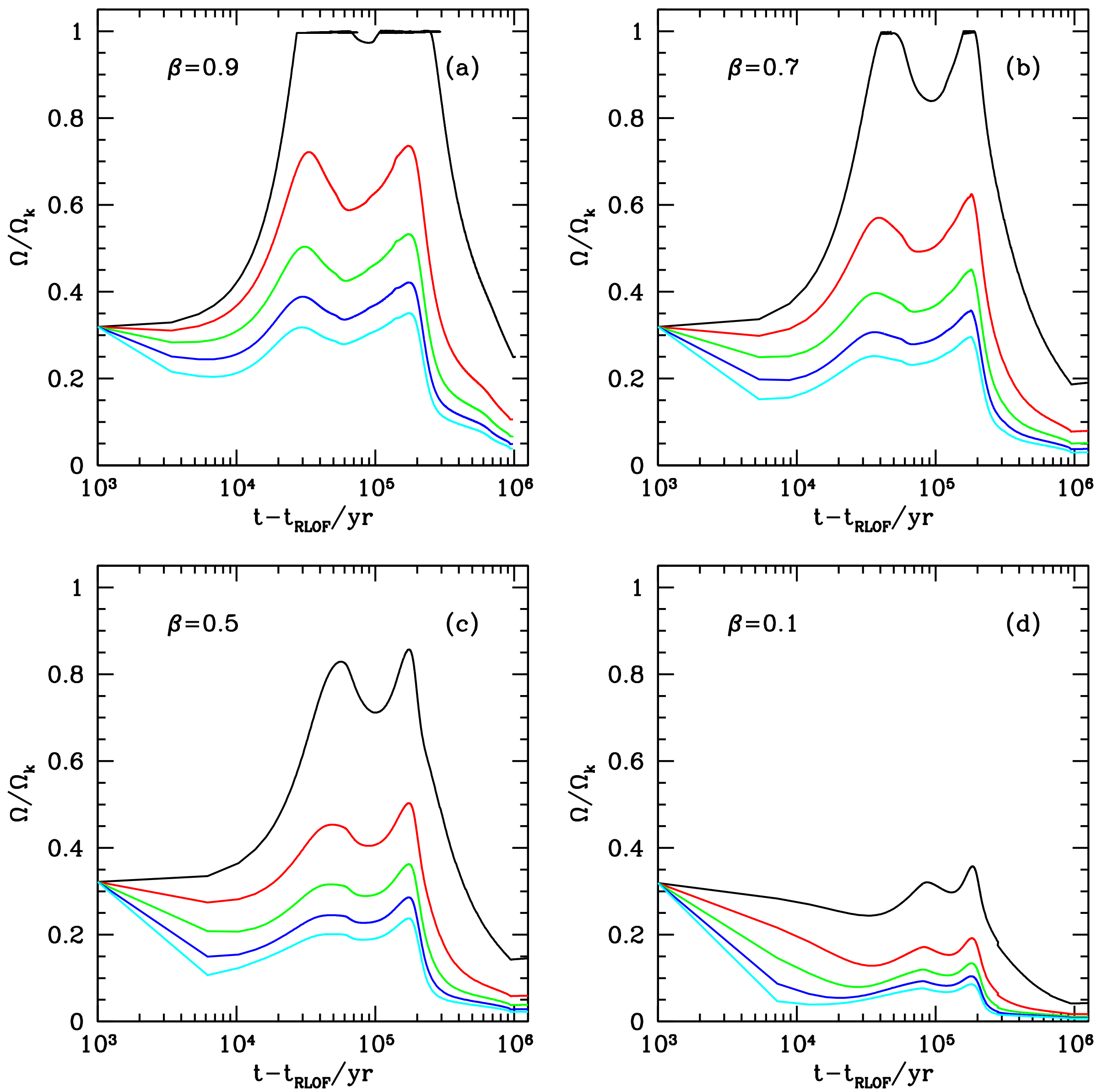

Figure 7. Variation of Ω/Ω_k, the fractional angular velocity of a gainer of initial mass $3\mathrm{M}_\odot$, with time elapsed since the onset of RLOF for (a) $\beta = 0.9$, (b) $\beta = 0.7$, (c) $\beta = 0.5$ and (d) $\beta = 0.1$ with $B_\mathrm{s} = 1$, 2, 3, 4 and 5 kG, from top to bottom in each panel.

Although there is evidence that magnetic winds brake the spin of stars, the underlying physics that produces the magnetic fields is not yet fully understood. There is a distinction between the magnetic properties of stars on the upper and lower main sequence. In the case of the Sun and solar-like stars the combination of a convective envelope and rotation is thought to generate the observable magnetic fields by an $\alpha-\Omega$ dynamo, the strength of which depends upon the stellar angular velocity. However, in contrast, only a minority of early-type stars, such as the Ap and Bp stars have observable magnetic fields. Many attempts have been made to explain these phenomena (for example Alecian et al. 2007; Ekström et al.

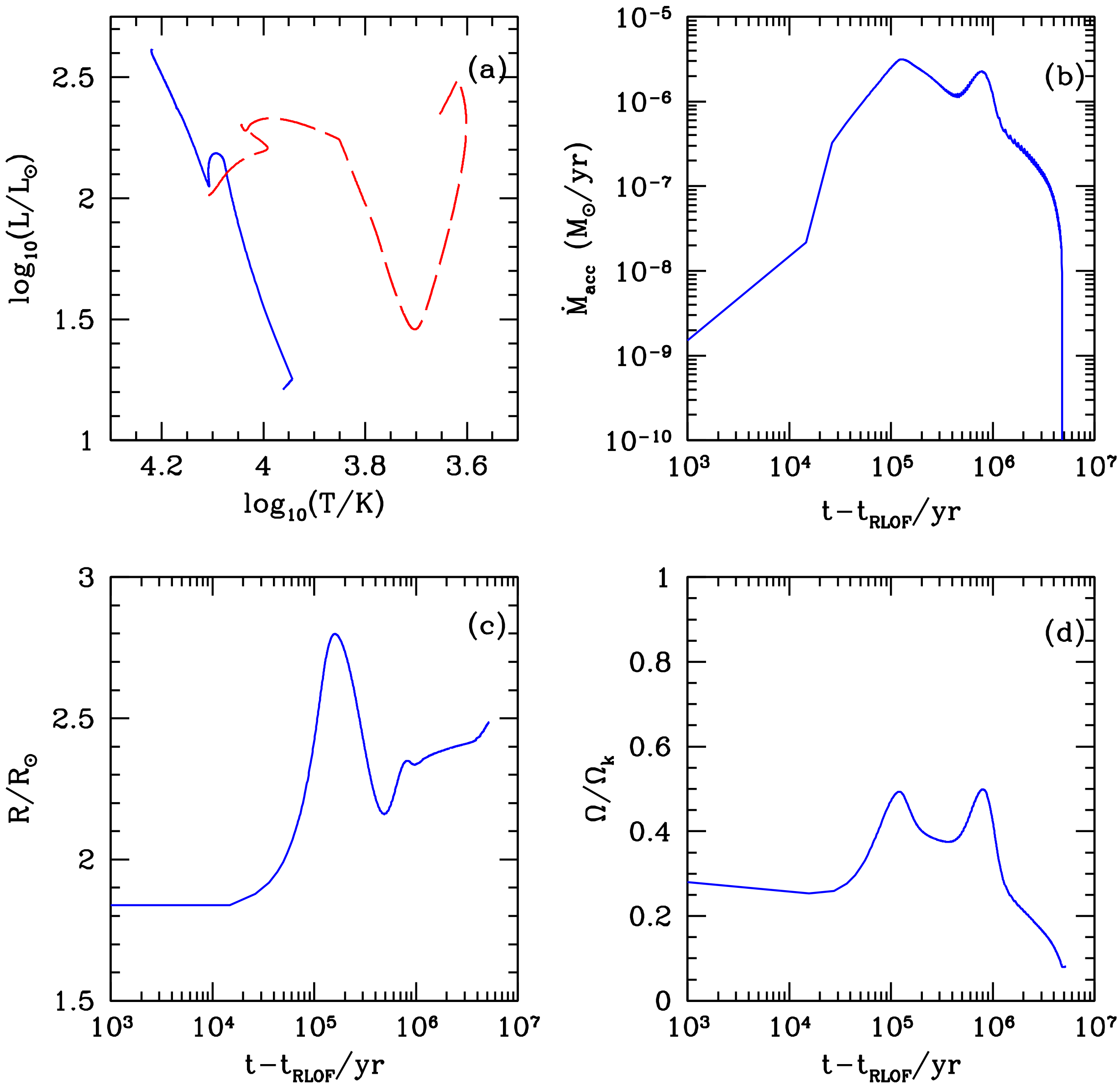

Figure 8. Similar to Fig. 6 but evolution of a binary star with initial masses of 3.2 and $2\,M_\odot$ and orbital period of 5 d with $\beta = 0.9$ and $B_s = 1.5$ kG. In (a) the dashed line is the track of the initially more massive donor and the solid line that of the gainer in an Hertzsprung–Russell diagram. Panels (b), (c) and (d) show the accretion rate, radius and Ω/Ω_k of the gainer as a function of time since the onset of RLOF.

2008; Ferrario et al. 2009). The primaries in most Algols, especially those with discs, are late B or early A type stars and have radiative envelopes. Stellar models confirm that the envelope is convectively stable in massive stars. Therefore solar-like concepts of dynamo operation are not directly applicable to these stars with radiative envelopes. Furthermore, there is no observational evidence of the presence of active regions on the surfaces of A and B stars. The origin of any magnetic dynamo which feeds energy into winds in early type stars

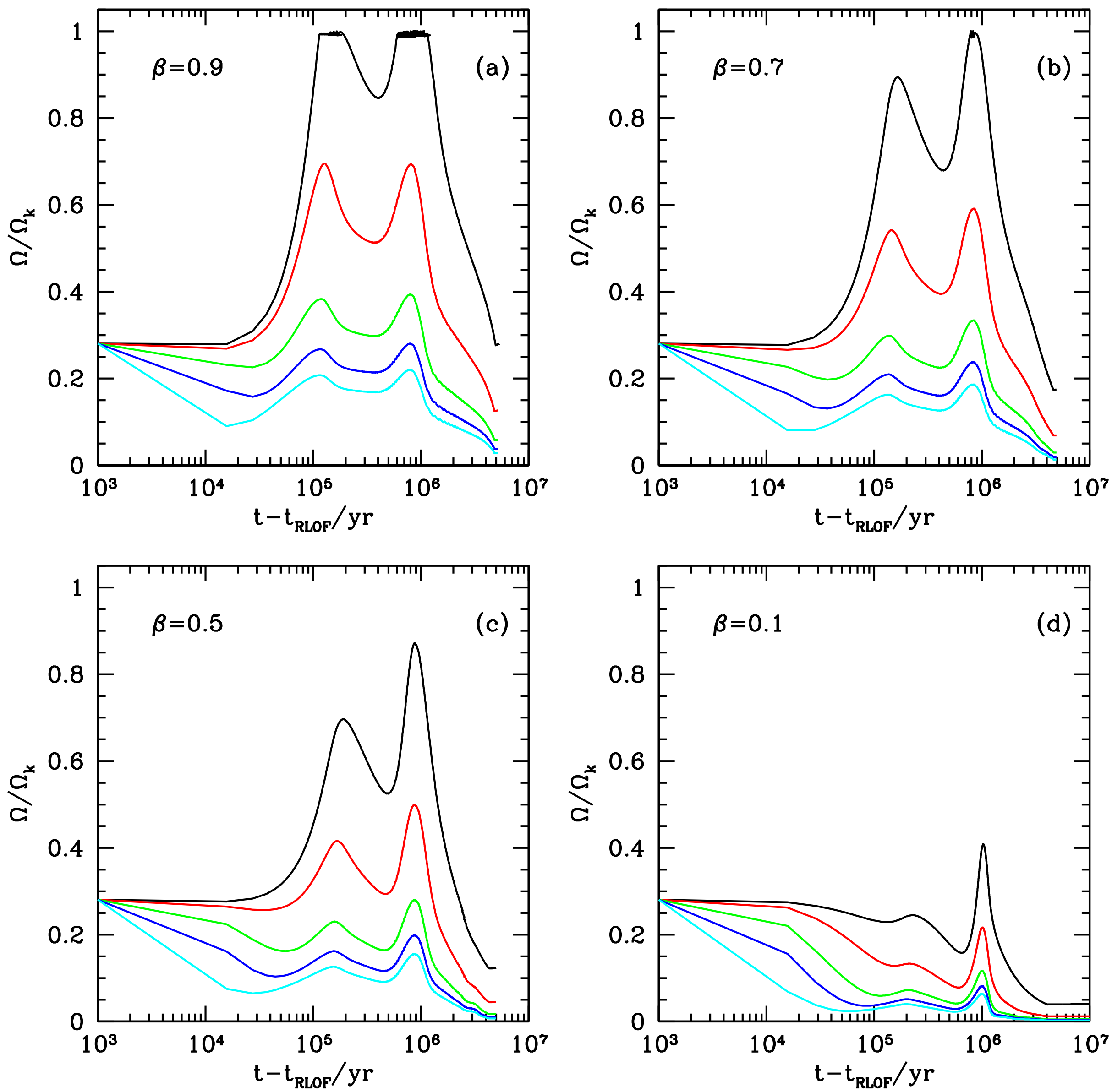

Figure 9. Similar to in Fig. 7 but for initial masses of $3.2+2\,\mathrm{M}_{\odot}$ and period $P=5\,\mathrm{d}$, $\beta=0.9$, 0.7, 0.5, and 0.1 and $B_{\mathrm{s}}=0.5$, 1, 2, 3 and 4 kG.

is unclear. Similar problems also exist for the explanation of the solid-body rotation profile within the radiative layers of the Sun (Chaplin et al. 2001).

While there is a growing body of observational evidence (Donati et al. 2006; MacDonald & Mullan 2004) that early type stars have measurable magnetic fields, no attempt has led to a comprehensive theory which explains both the origin of and the sustaining mechanism of the magnetic field. Two leading possibilities are the fossil field theory (Cowling 1945) and the dynamo. Existing theories of dynamo generated fields focus on different assumptions but propose that dynamos operate either in the fully convective cores or in the differentially rotating radiative envelope. MacDonald & Mullan (2004) report serious difficulties with the

core dynamo hypothesis suggested by Charbonneau & MacGregor (2001) because the core must create magnetic fields that are much stronger than equipartition values in order to reach to the surface.

Spruit (1999) argues that a principle ingredient of dynamo operation in a star is rapid rotation. This is certainly available in massive stars. While the driving mechanism of magnetic field generation is based on hydrodynamical instabilities in solar type stars, similar instabilities in the radiative stars may be produced by the magnetic fields themselves. Examples are the Parker and Tayler instabilities (Parker 1979; Tayler 1973). Spruit (2002) formulated a dynamo mechanism for a differentially rotating star in which Tayler instability replaces the role of convection in closing the field amplification loop. The azimuthal component of the magnetic field grows until it reaches a critical strength by winding up an initially very small radial component in a non-convective zone. At that point the Tayler instability operates on a very short time-scale, of the order of Alfvén crossing time, to regenerate the radial field. The result is a predominantly toroidal field and a closed dynamo loop. Recent numerical simulations by Braithwaite & Spruit (2004) and Braithwaite & Nordlund (2006) showed that a stable configuration can be reached within a non-convective star on an Alfvén time-scale from an arbitrary initial magnetic field. The Spruit-Tayler mechanism is not the only one that operates in non-convective material. Balbus & Hawley (1994) have proposed a magneto-rotational instability which works well for accretion discs without convection.

Fig. 10 shows the internal structure of the gainer during the mass transfer for our system with initial masses of 5 and $3\,\mathrm{M}_\odot$. The gainer has a substantial convective core and an almost constant mass radiative envelope throughout the mass accretion.

As Spruit (2002) pointed out, differential rotation in single stars provides a finite amount of energy for generating magnetic fields so we might expect that the dynamo to cease once the rotation profile has been smoothed out. In the case of our semi-detached binary stars with discs, the energy in differential rotation can be continuously supplied from the disc material which has high specific angular momentum relative to the star as we discussed in section 3. Hence, if a Spruit-Tayler type dynamo operates in this case, magnetic fields are regenerated as long as mass transfer continues. According to our assumption that the wind is accelerated to the stellar escape velocity (equation 12) and leaves the system at the Alfvén radius, the rate of energy required to be fed into the wind is given by

$$L_{\mathrm{w}} \approx \frac{GM\dot{M}_{\mathrm{w}}}{R_{\mathrm{A}}}. \tag{18}$$

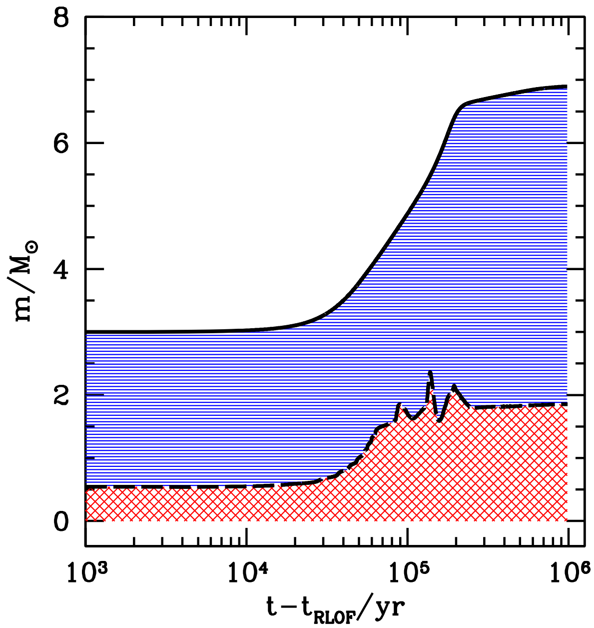

Figure 10. Radiative and convective zones with mass m in the gainer in our system of initially $5+3\,\mathrm{M}_\odot$, orbital period 5 d and $\beta = 0.9$. Convective (cross shaded) and non-convective (horizontal shaded) regions of the gainer during the mass transfer are shown with respect to the time elapsed since the onset of RLOF. The envelope of the gainer is always convectively stable.

This can be provided via the dynamo from the highly energetic disc material which continuously supplies energy to the star. Roughly speaking, $\Delta\Omega \approx R\,d\Omega/dr$ is the change of angular velocity between centre and outer edge of the gainer or across its surface from pole to equator. The shear energy which can be tapped is (Tout & Pringle 1995)

$$E_{\rm sh} \approx \frac{1}{2}k^2\left(\frac{GM^2}{R}\right)\left(\frac{\Delta\Omega}{\Omega}\right)\left(\frac{\Omega}{\Omega_{\rm k}}\right)^2. \tag{19}$$

If $\Delta\Omega \approx \Omega$ we can evaluate $E_{\rm sh}/L_{\rm w}$ to estimate the time over which the shear energy could sustain the wind, even if it were not replenished, to be $10^5 - 10^6$ yr. This is similar to the timescale over which mass transfer takes place so the shear energy is a good candidate for supplying energy to the dynamo during the mass transfer phase. The quantity $\tau_{\rm dyn} = E_{\rm sh}/L_{\rm w}$ during the mass transfer is plotted against the time since the onset of RLOF in Fig. 11.

Tout & Pringle (1992) developed a model based on the idea that the dynamo process creates not only magnetic field also leads a continual expulsion of magnetic flux from the star. This flux, they assume, provides the mechanical output of energy that drives stellar wind. They developed schematic dynamo equations and give a rough expression for this rate as

$$L_{\rm w} \approx \frac{d}{dt}\left(\frac{B_\phi^2}{8\pi}\right)_{\rm loss}\frac{4}{3}\pi R^3 \approx \frac{B_\phi^2}{4\pi}\tau_\phi^{-1}\frac{4}{3}\pi R^3, \tag{20}$$

where τ_ϕ is the decay time-scale of the toroidal field component B_ϕ. It is assumed to be equal to $\tau_{\rm g}$, the growth time-scale on which the dynamo reaches equilibrium, given by (Spruit 2002,

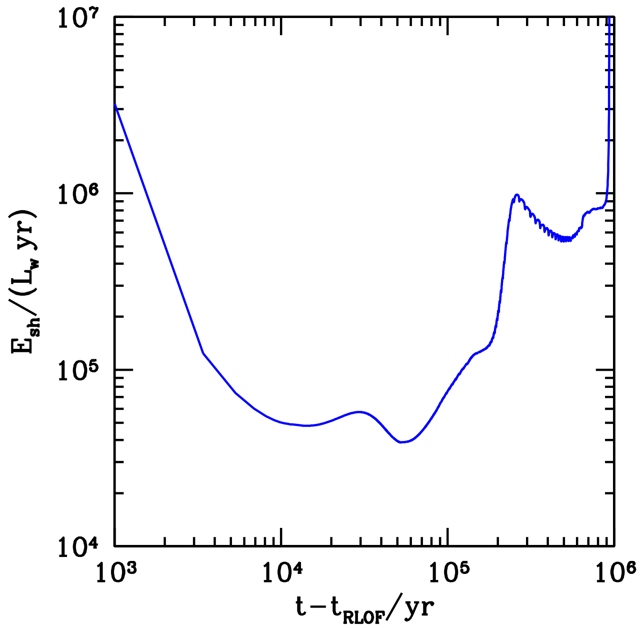

Figure 11. Variation of the dynamo timescale $\tau_{\rm dyn} = E_{\rm sh}/L_{\rm w}$ with time elapsed since the onset of RLOF. The shear energy seems to be sufficient to sustain the required wind for $10^5 - 10^6$ years at any stage.

Eq 17)

$$\tau_\phi \approx \tau_{\rm g} \approx \Omega/\omega_{\rm A}^2 \approx q_r^{1/2}. \tag{21}$$

Combining equations 18 and 20 and using equation 21 with equation 19 of Spruit (2002), we can estimate the mass-loss rate in the wind for mean values of $r \approx R$ and $\rho \approx \bar{\rho}$,

$$\frac{\dot{M}_{\rm w}}{M} \approx q_r^2 \Omega \left(\frac{\Omega}{\Omega_k}\right)^2 \left(\frac{\Omega}{N}\right)^{1/2} \left(\frac{K}{R^2 N}\right)^{1/2}. \tag{22}$$

In this formula the quantity N is the Brunt-Väisälä frequency, $q_r = d\ln\Omega/d\ln r$ is dimensionless gradient of rotation and K is the thermal diffusivity. This equation is derived under the assumption that almost all the flux lost is transferred to the wind. Therefore, equation 22 is a theoretical upper limit to the mass lost in the wind. We find that such a fully efficient Spruit-Tayler dynamo can support a wind up to $0.01\,{\rm M}_\odot\,{\rm yr}^{-1}$. In this estimate we use mean values of the parameters $N \approx 10^{-3}\,{\rm s}^{-1}$, $K \approx 10^8 - 10^9{\rm cm}^2\,{\rm s}^{-1}$ and assume the differential rotation gradient $q_{\rm r} \approx \Delta\Omega/\Omega \approx 1$.

Matt & Pudritz (2005, 2008a,b) have also studied accretion powered stellar winds, both analytically and with two dimensional magnetic wind solutions. Although they are interested in T Tauri type stars, they claim that their models are independent of dynamo mechanism. Based on two-dimensional simulation they found that the field strength outside the star falls off as if with $n \approx 3.24$ which is very similar to the simple dipolar field decay with $n = 3$. We compare the values of the Alfvén radius we calculate with those of Matt & Pudritz (2008a)

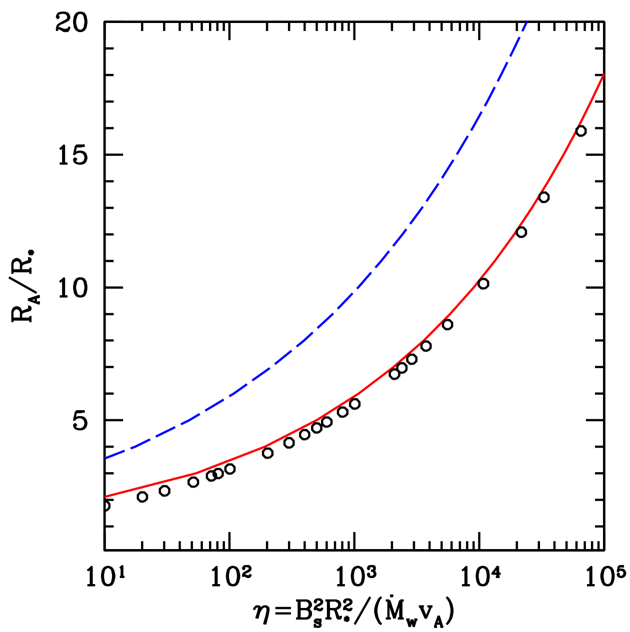

Figure 12. Comparison of our calculated Alfvén radii (open circles) with those of Matt & Pudritz (2008a, dashed line) and ud-Doula & Owocki (2002, solid line) for a range of values of the wind confinement parameter η.

and ud-Doula & Owocki (2002) in Fig. 12. In this comparison we used the dimensionless wind magnetic confinement parameter, η which characterizes the ratio of magnetic field energy density to the kinetic energy density of the wind. We find a good agreement with that of ud-Doula & Owocki (2002). However the Alfvén radii calculated by us seem to be a factor of two smaller than those of Matt & Pudritz (2008a).

4 CONCLUSIONS

It has been known for some time that many long-period Algol systems have accretion discs. Accreting material from such a disc should increase the spin rate of the more massive component up to its break-up speed as soon as even a small fraction of the mass has been transferred (de Mink, Pols & Glebbeek 2007). All the classical Algols have a less massive evolved and a more massive main-sequence component. Therefore a substantial amount of mass from the initially more massive star must be either lost or transferred to its companion. The angular velocities of the more massive components in many Algols are measured with great accuracy. These measurements show that the gainers rotate somewhat more slowly than their break-up rates. Thus there must be a mechanism which removes spin angular momentum from the rapidly rotating hot star. We have demonstrated that tidal interaction between the components and the orbit is too weak to do this fast enough. We show, however,

that magnetic braking, driven by a magnetic dynamo that is maintained by the accretion itself, can remove sufficient angular momentum. MacDonald & Mullan (2004) hypothesized that a dynamo operating in a sheared radiative region can generate flux tubes which are able to rise the surface of the star. A shear dynamo in the extended radiative envelope of a massive star can therefore serve as an efficient supplier of magnetic flux to the surface of the star. We propose a similar self-consistent model in which a dynamo operates in shear-unstable material throughout the radiative envelopes of the gainers in Algols with orbital periods longer than $4 - 5\,\mathrm{d}$. Such stars can lose angular momentum in magnetized stellar winds, leading to non-conservative angular momentum evolution.

Under this non-conservative evolution, an Algol system continues to evolve with relatively little mass loss at a rate $\dot{M}_{\mathrm{w}} \approx 0.1\dot{M}_{\mathrm{acc}}$ but corotating to a relatively large Alfvén radius R_{A}. When it reaches the classical Algol phase the less massive component is observed to be more evolved than the massive one. Spruit-Tayler instabilities seem most likely to be responsible for the operation of a magnetic dynamo in massive stars with radiative envelopes (Mullan & MacDonald 2005). However we need to construct two dimensional models with an accretion disc to test how such a dynamo really operates in Algols. Such numerical models could also supply more realistic Alfvén radii based on the field geometry. Using such detailed models we should be able to find an equilibrium spin-ratio which can explain the observations in Fig 2. We might also take into account the effect of wind induced hydrodynamic instabilities suggested by Lignieres, Catala, & Mangeney (1996) which may also effect the differential rotation parameter.

Using a very simple model we computed the spin angular momentum evolution of gainers with discs in two systems with an initial orbital period of 5 d but different masses. The results show that even a small amount of mass, about 10 per cent of the transferred material, lost by the gainer with a magnetic field of 1 kG is sufficient to slow down the star to below its break-up velocity. As the magnetic field strength increases the rotational velocity of the star decreases for the same amount of mass loss.

ACKNOWLEDGEMENTS

AD is grateful to the Institute of Astronomy, Cambridge for hospitality and the Scientific and Technological Research Council of Turkey (TÜBİTAK) for PhD fellowships. CAT thanks Churchill College for his Fellowship and is very grateful for the hospitality of IUCAA, Pune

and the University of Canterbury where some work on this manuscript was carried out. This work has been supported in part by (TÜBİTAK) through grant no 109708. We thank the referee for his or her helpful comments for improving this manuscript.

REFERENCES

Alecian E., Wade G. A., Catala C. et al., 2007, in Bouvier J., Appenzeller I., eds, Proc. IAU Symp. 243, Star-Disk Interaction in Young Stars. Cambridge Univ. Press, Cambridge, p. 43

Armitage P. J., Clarke C. J., 1996, MNRAS, 280, 458

Balbus S. A., Hawley J. F., 1994, MNRAS, 266, 769

Braithwaite J., Spruit H. C., 2004, Nature, 431, 819

Braithwaite J., Nordlund Å., 2006, A&A, 450, 1077

Chaplin W. J., Elsworth Y., Isaak G. R., Marchenkov K. I., Miller B. A., New R., 2001, MNRAS, 327, 1127

Charbonneau P., MacGregor K. B., 2001, ApJ, 559, 1094

Chen W.-C., Li X.-D., Qian S.-B., 2006, ApJ, 649, 973

Cowling T. G., 1945, MNRAS, 105, 166

Crawford J. A., 1955, ApJ, 121, 71

Darwin G. H. 1879, Phil. Trans. R. Soc. London, 170, 1

de Mink S. E., Pols O. R., Glebbeek E., 2007, AIPC, 948, 321

Donati J.-F., et al., 2006, MNRAS, 370, 629

Eggleton P. P., 1971, MNRAS, 151, 351

Eggleton P. P., 2000, New Astron. Rev., 44, 111

Eggleton P. P., 2006, Evolutionary Processes in Binary and Multiple Stars. Cambridge Univ. Press, Cambridge

Ekström S., Meynet G., Maeder A., Barblan F, 2008, A&A, 478, 467

Etzel P. B., Olson E. C., 1993, AJ, 106, 1200

Ferrario L., Pringle J. E., Tout C. A., Wickramasinghe D. T., 2009, MNRAS, 400, 71L

Flannery B. P., 1975, MNRAS, 170, 325

Ghosh P., Lamb F. K., 1978, ApJ, 223, L83

Gimenez A., 1996, Rev. Mex. Astron. Asrofis. Ser. Conf., 5, 21

Glazunova L. V., Yushchenko A. V., Tsymbal V. V., Mkrtichian D. E., Lee J. J., Kang Y. W., Valyavin G. G., Lee B.-C., 2008, AJ, 136, 1736

Hansen K., McNamara D. H., 1959, ApJ, 130, 791

Hartmann L., Stauffer J. R., 1989, AJ, 97, 873

Hoyle F., 1955, Frontiers of Astronomy. Heinemann, London

Hurley J. R., Tout C. A., Pols O. R., 2002, MNRAS, 329, 897

İbanoğlu C., Soydugan F., Soydugan E., Dervişoğlu A., 2006, MNRAS, 373, 435

Lignieres F., Catala C., Mangeney A., 1996, A&A, 314, 465

Lubow S. H., Shu F. H., 1975, ApJ, 198, 383

MacDonald J., Mullan D. J., 2004, MNRAS, 348, 702

McNamara D. H., 1957, PASP, 69, 574

Maeder A., 2009, Physics, Formation and Evolution of Rotating Stars. Springer, Berlin

Manzoori D., 2008, Ap&SS, 318, 57

Matt S., Pudritz R. E., 2005, ApJ, 632, L135

Matt S., Pudritz R. E., 2008, ApJ, 678, 1109

Matt S., Pudritz R. E., 2008, ApJ, 681, 391

Mestel L., 1968, MNRAS, 138, 359

Mestel L., Spruit H. C., 1987, MNRAS, 226, 57

Mullan D. J., MacDonald J., 2005, MNRAS, 356, 1139

Mukherjee J., Peters G. J., Wilson R. E., 1996, MNRAS, 283, 613

Olson E. C., Bell D. J., 1989, PASP, 101, 907

Packet W., 1981, A&A, 102, 17

Parker E. N., 1979, Cosmical Magnetic Fields: their Origin and their Activity. Oxford Univ. Press, Oxford

Pols O. R., Tout C. A., Eggleton P. P., Han Z., 1995, MNRAS, 274, 964

Pols O. R., Schroder K.-P., Hurley J. R., Tout C. A., Eggleton P. P., 1998, MNRAS, 298, 525

Richards M. T., Albright G. E., 1999, ApJS, 123, 537

Soydugan F., Frasca A., Soydugan E., Catalano S., Demircan O., İbanoğlu C., 2007, MNRAS, 379, 1533

Spruit H. C., 1999, A&A, 349, 189

Spruit H. C., 2002, A&A, 381, 923

Stancliffe R. J., Eldridge J. J., 2009, MNRAS, 396, 1699

Stępień K., 1995, MNRAS, 274, 1019

Stępień K., 2000, A&A, 353, 227

Stępień K., 2002, A&A, 383, 218

Stothers R., Lucy L. B., 1972, Nat, 236, 218

Tayler R. J., 1973, MNRAS, 161, 365

Tout C. A., Pringle J. E., 1992, MNRAS, 256, 269

Tout C. A., Hall D. S., 1991, MNRAS, 253, 9

Tout C. A., Pringle J. E., 1995, MNRAS, 272, 528

Tout C. A., Aarseth S. J., Pols O. R., Eggleton P. P., 1997, MNRAS, 291, 732

ud-Doula A., Owocki S. P., 2002, ApJ, 576, 413

van Hamme W., Wilson R. E., 1990, AJ, 100, 1981

Weber E. J., Davis L. J., 1967, ApJ, 148, 217

Zahn J.-P., 2005, in Claret A., Giménez A., Zahn J.-P., eds, ASP Conf. Ser. Vol. 333, Tidal Evolution and Oscillation in Binary Stars: Third Granada Workshop on Stellar Structure. Astron. Soc. Pac., San Fransisco, p. 4